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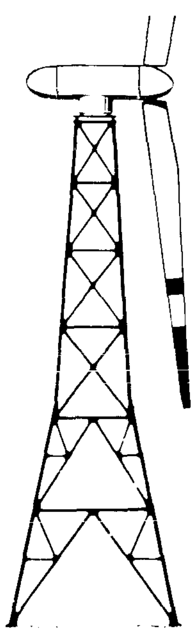
200-KILOWATT WIND TURBINE PROJECT

A part of the

U.S. DEPARTMENT OF ENERGY
Federal Wind Energy Program

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

June 1979



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Wind-energy systems have been used for centuries as a source of energy for man. The applications have ranged from pumping water and grinding grain to generating electricity. At times considerable interest existed in both the United States and Europe in developing large wind-driven generating systems as a source of electric power. However, interest in such systems declined because they were not cost competitive with the fossil fuel systems of that era. Also, these efforts were generally privately financed and thus suffered from the lack of a sustained research and development effort.

The continuing increase in energy requirements, increases in fuel costs, depletion of our fuel reserves, and dependence on foreign sources have made it necessary to investigate and develop alternate energy sources. Wind energy, being a clean, nondepletable source of energy, could be a viable alternate source. Thus, a Federal Wind Energy Program was established to enable research and development on the many applications and concepts of wind energy systems. This program, which originated at the National Science Foundation, is currently directed and funded by the newly created Department of Energy.

One phase of the Federal Wind Energy Program is to develop the technology necessary for the successful design, fabrication, and operation of large, horizontal wind turbine systems. This phase of the program is being managed by the National Aeronautics and Space Administration's Lewis Research Center for the Department of Energy. The four 200-kilowatt wind turbines described in this report compose the first of four separate systems currently under development. Wind turbines of the two other systems, although similar in design, will be larger in both physical size and rated power generation.

The overall objective of this project is to obtain early operation and performance data while gaining initial experience in the operation of large, horizontal-axis wind turbines in typical utility environments. Several of the key issues that will be addressed include the following:

- Impact of the variable power output (due to varying wind speeds) on the utility grid
- Compatibility with utility requirements (voltage and frequency control of generated power)
- Demonstration of unattended, fail-safe operation
- Reliability of the wind turbine system
- Required maintenance
- Initial public reaction and acceptance

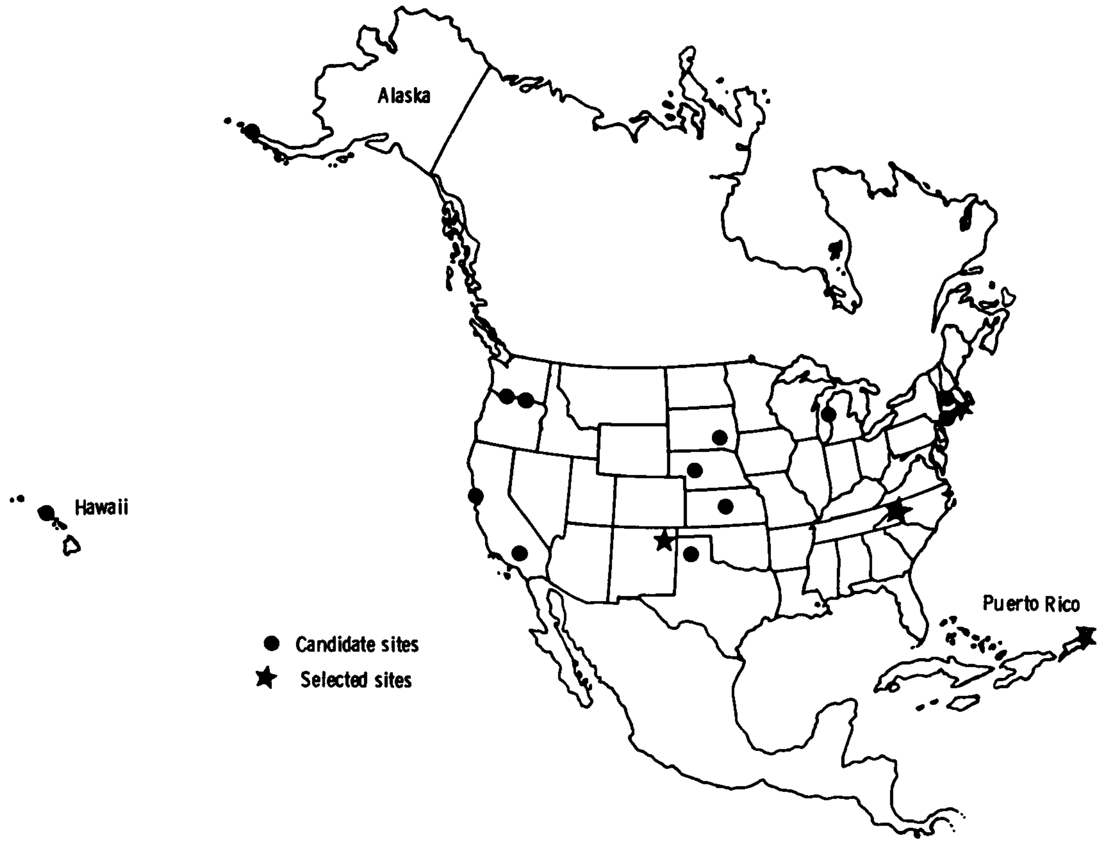
approach

The approach used in managing this project, in addition to satisfying the overall objective, fulfilled the following two requirements:

• Involve utility companies in the project not only to provide a test site but to identify their particular requirements while gaining direct operational experience. This is necessary for their potential role of successful owner/operators of future wind turbine systems.

• Build up industry capability in the design, fabrication, and operation of wind turbine systems. This is necessary to achieve rapid commercial application once the technology has been developed.

The selection of utility company sites for experimental wind turbines was made on the basis of proposals submitted by the utility companies. Over sixty-four utility companies submitted detailed information about their company and the site they proposed for installation of a wind turbine. These proposed sites were evaluated on the basis of available wind energy, need for supplemental power, interest in supplying personnel for the program, and variations in climatic and topographical conditions. The 17 sites selected for more detailed evaluation are shown and listed in figure 1 along with the participating utility company. Identical meteorological towers and wind instrumentation were installed at each site so that the wind potential of the sites could be evaluated on a common basis.



Site	Organization	Site	Organization
Cold Bay, Alaska	Alaska Bussell Electric Co.	Montauk Point, Long Island, New York	Long Island Lighting Co.
Point Arena, California	Pacific Gas and Electric Co.	Boone, North Carolina[b]	Blue Ridge Electrical Membership Corporation
San Gorgonio Pass, California	Southern California Edison	Boardman, Oregon	Portland General Electric Co.
Oahu, Hawaii[a]	Hawaiian Electric Co.	Island of Culebra, Puerto Rico[a]	Puerto Rico Water Resources Authority
Russell, Kansas	City of Russell, Kansas	Block Island, Rhode Island[a]	Block Island Power Co.
Holyoke, Massachusetts	City of Holyoke Gas and Electric Department	Huron, South Dakota	East River Power Cooperative
Ludington, Michigan	Consumers Power Co.	Amarillo, Texas	Southwestern Public Service Co.
Kingsley Dam, Nebraska	Central Nebraska Public Power and Irrigation District	Augspurger Mountain, Washington	Bonneville Power Administration
Clayton, New Mexico[a]	Town of Clayton		

[a]Four sites selected for 200-kW systems.
[b]Site selected for future installation of 2000-kW system.

Figure 1. - Candidate wind turbine sites.

The four sites selected for the installation of the 200-kilowatt wind turbine shown in figure 2 are Clayton, New Mexico, Island of Culebra, Puerto Rico, Block Island, Rhode Island, and Oahu, Hawaii. The fuels used to produce the power along with the peak power demands for the participating utility companies are as follows:

Site	Fuel	Peak power, kW
Clayton	Diesel/natural gas	3 800
Culebra	Diesel (backup)	1 200
Block Island	Diesel	1 400
Oahu	Oil	900 000

Except for Culebra, all utilities are isolated and have no tie with neighboring grids. Culebra just recently installed an underwater cable to bring power from the mainland. The diesel-powered generators once used to provide the power now serve as a backup in the event the underwater cable should fail.

The significant events that summarize the operational history of the Clayton machine shown in figure 3(a) are as follows:

- First rotation was accomplished on November 30, 1977.
- In January 1978, the machine completed its first 100 hours of operation.
- In March 1978, the machine was

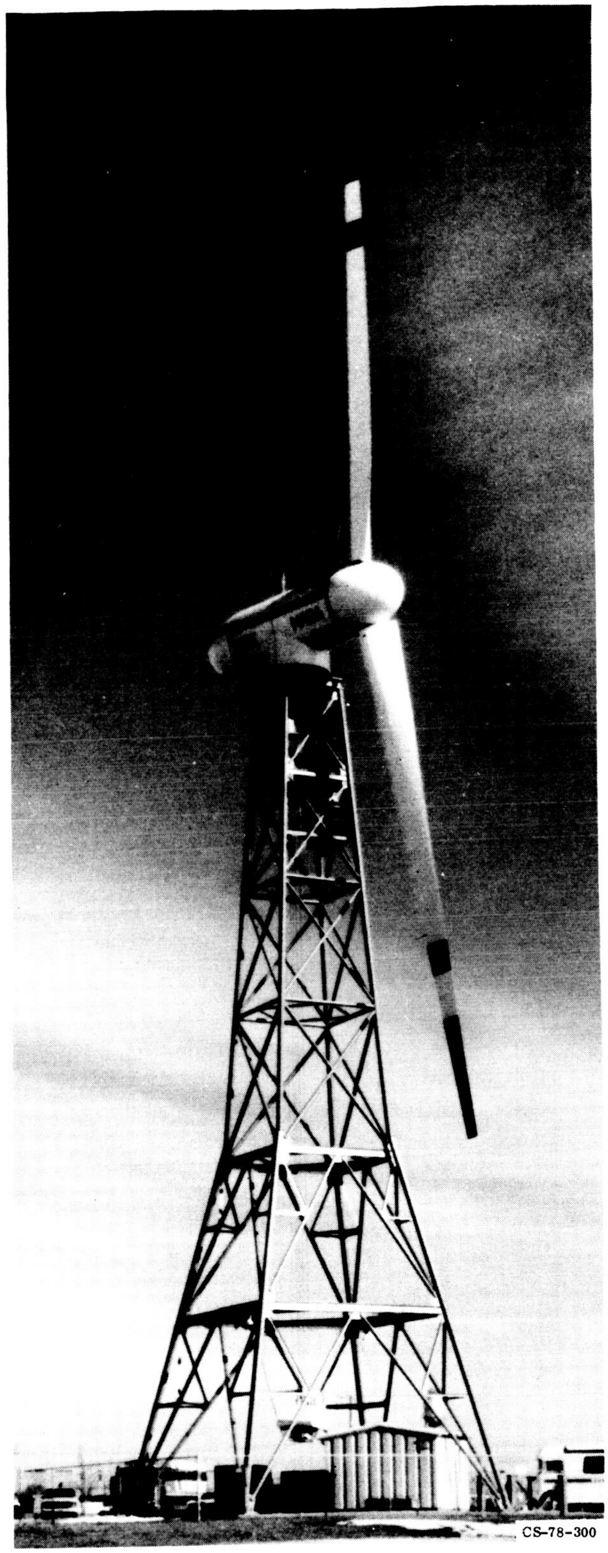
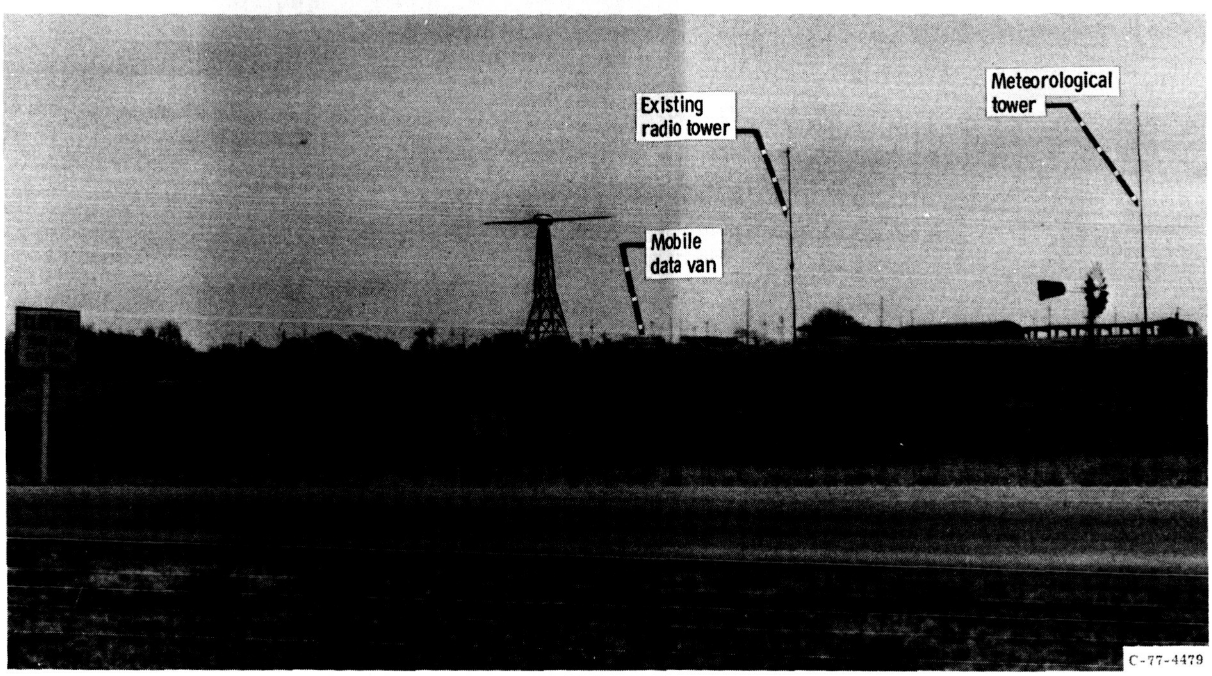


Figure 2. - 200-Kilowatt wind turbine.

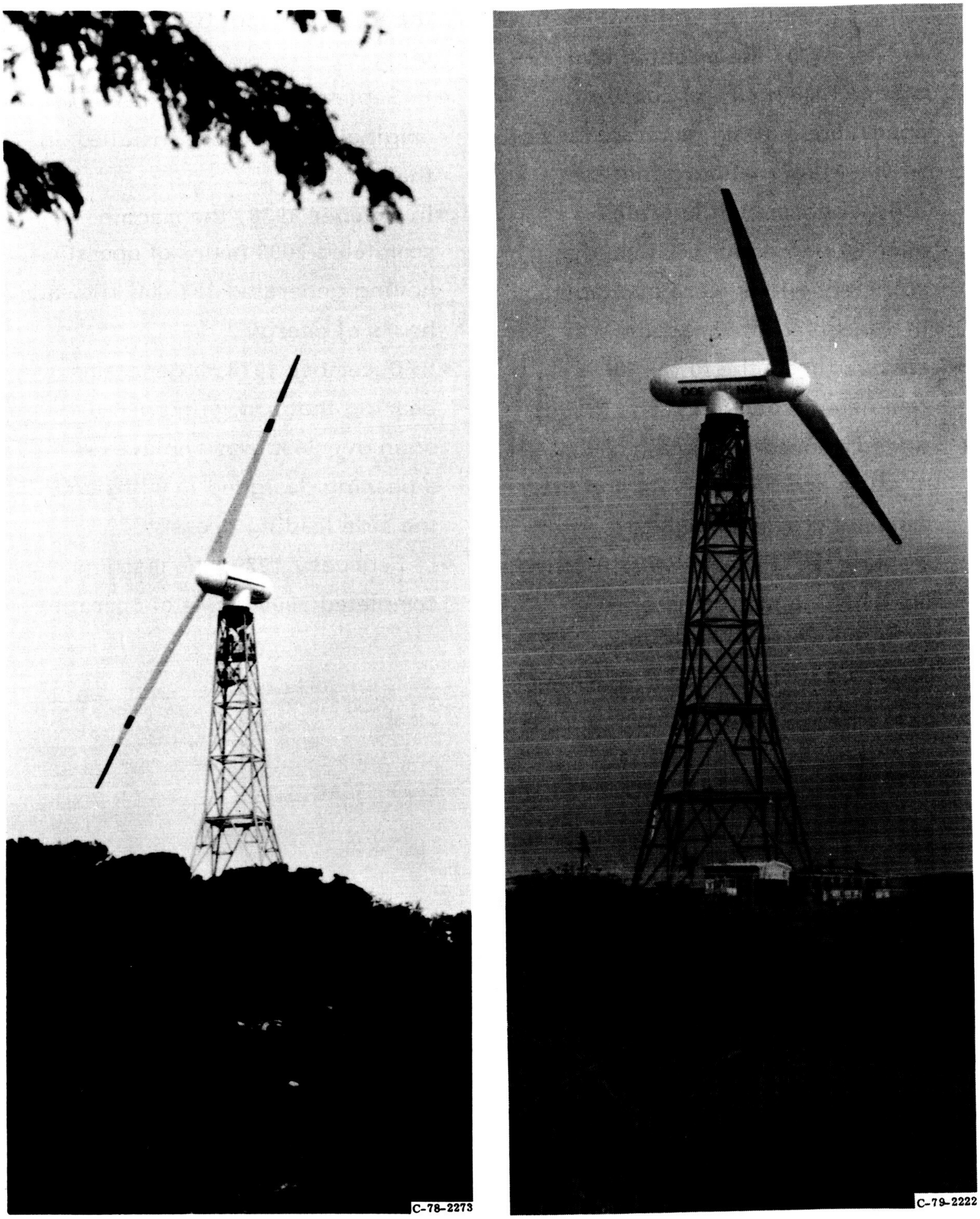
turned over to the utility.

- In May 1978, the machine completed 1000 hours of successful operation, having generated over 94 000 kilowatt-hours into the utility network; it operated over 80 percent of the time that sufficient winds were available.
- In June 1978, the machine was removed from the tower for a complete inspection. The blades were removed for repair of the missing and loose rivets and the material cracks observed. After a spare set of blades was installed, the machine was reinstalled on the tower and put back into service.
- In September 1978, the repaired original blades were installed on the machine.
- In October 1978, the machine completed 2000 hours of operation, having generated 181 000 kilowatt-hours of energy.
- In December 1978, a generator bearing that had failed because of an overload was replaced with a bearing designed to withstand the side loading present.
- In February 1979, the machine completed 3000 hours of operation,



(a) Clayton.

Figure 3. - Overall views of Clayton, Culebra, and Block Island wind turbine sites.



(b) Culebra.

(c) Block Island.

Figure 3. - Concluded.

having generated 286 000 kilowatt-hours of energy.

- In March 1979, the fluid coupling was replaced after the unit developed fatigue cracks.
- In April 1979, the machine was shut down for a complete blade inspection and repair.
- As of April 19, 1979, the machine had completed 3900 hours of operation and had generated 380 000 kilowatt-hours of energy.

The wind turbine at Culebra (shown in fig. 3(b)) has the following significant milestones:

- First rotation was accomplished on June 26, 1978.
- In September 1978, the machine completed its first 100 hours of operation.
- In January 1979, the machine was turned over to the utility.
- In May 1979, the machine was shut down to enable a complete blade inspection and subsequent repair. This repair was similar to that performed on the Clayton machine blades in June 1978.
- As of May 4, 1979, the machine had completed 573 hours of operation and had generated 83 600 kilowatt-hours of energy.

The wind turbine at Block Island experienced its first rotation on May 1, 1979, and is currently undergoing checkout operations. An overall view of the Block Island site is shown in figure 3(c).

Procurement of the long lead components for the Oahu machine has been initiated. Site preparation work is scheduled for the fall of 1979 with the installation of the machine scheduled for the spring of 1980.

The overall wind turbine design, component specifications, engineering drawings, and testing requirements and procedures were established by the Lewis Research Center. Project responsibilities are as follows:

Wind turbine site	Procurement/ fabrication	Assembly/ shop test	Installation
Clayton	Lewis	Lewis	Contractor
Culebra	Lewis	Contractor	Contractor
Block Island	Contractor	Contractor	Contractor
Oahu	Contractor	Contractor	Contractor

The Special Services Division of Westinghouse Electric Corporation was selected by competitive bidding to be the contractor. Both Lewis and contractor personnel will be involved in the estimated 3-month checkout operation for each wind turbine. Following the acceptance testing for each wind turbine, the participating utility company will be responsible for maintaining the operation of each wind turbine for 2 years.

description

operation

The rated power output of the wind turbine is 200 kilowatts, which is achieved at a turbine rotor speed of 40 rpm and a rated wind speed of 18.3 mph. The rated wind speed is defined as the lowest wind speed at which full power is achieved. The power output as a function of wind speed, shown in figure 4, is regulated by varying the pitch angle of the blades. At wind speeds below cut-in and above cut-out the rotor blades are placed in a feathered position and no power is produced. The cut-in wind speed, defined as the lowest wind speed at which power can be generated, is 6.9 mph. The cut-out wind speed, defined as the lowest wind speed at which wind turbine operation would result in excessive blade stress, is 34.2 mph. All of these wind speeds are measured at a 30-foot elevation.

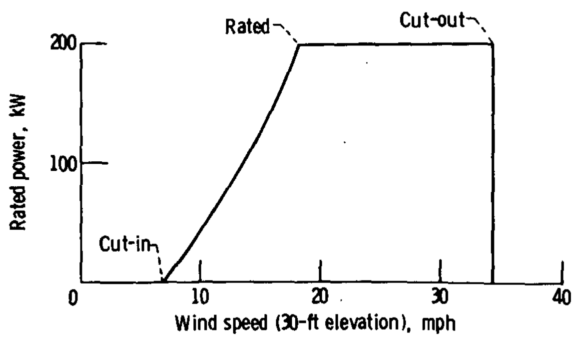


Figure 4. - Power output as function of wind speed.

mechanical system

The 200-kilowatt wind turbine system, shown schematically in figure 5, consists of the turbine rotor, nacelle, tower, hoist, and control building. The two propeller type rotor blades, which rotate about a horizontal axis, are located downstream of the tower. The drive train assembly, which converts the 40 rpm rotor speed to the 1800 rpm generator speed, is enclosed in a fiberglass nacelle for environmental protection. The nacelle and rotor assembly are positioned at the top of a tower to provide the necessary blade tip to ground clearance. The hoist provides access to the equipment mounted at the top of the tower. The onsite controls and electrical switchgear are housed in the control building at the base of the tower. A cutaway drawing of the tower mounted equipment with all major components identified is shown in figure 6. A photograph taken during the shop assembly of the Clayton machine, included as figure 7, shows the relative size and positioning of the various components. The primary design specifications and operating parameters are summarized in table I. Some of the components are now discussed in detail.

Blades. - The rotor blades are made of aluminum, except for the cylindrical blade root shank, which is made of steel. The blade, shown in figure 8, consists of a main load carrying spar and ribs covered by a thin sheet metal skin. The construction is similar to that of a conventional airplane wing.

Hub. - The rotor hub (shown in fig. 9) connects the blades to the low speed shaft and houses the pitch change mechanism. The hub is a rigid type; that is, the blade is rigidly attached to the hub and the blade is permitted only the pitch change degree of freedom. The hub transmits the torque developed by the rotor blades to the shaft and transmits all other blade loads into the bedplate through the low speed shaft bearings.

Pitch change assembly. - The pitch change assembly consists of a hydraulic supply, a rack and pinion actuator, and gears to rotate the blades in the hub. This type of pitch change mechanism is similar to that used in the aircraft industry on variable pitch propellers. As shown in figure 10, a pair of racks is moved linearly back and forth by hydraulic pressure. This pair of racks rotates a pinion that turns a master gear, which in turn rotates the blades through bevel gears bolted to the blade spindle. The hydraulic supply is mounted separately inside the front of the nacelle as shown in figure 6. Hydraulic fluid is brought into the main shaft through rotating seals and transmitted to the rack and pinion actuator mounted on the rotor

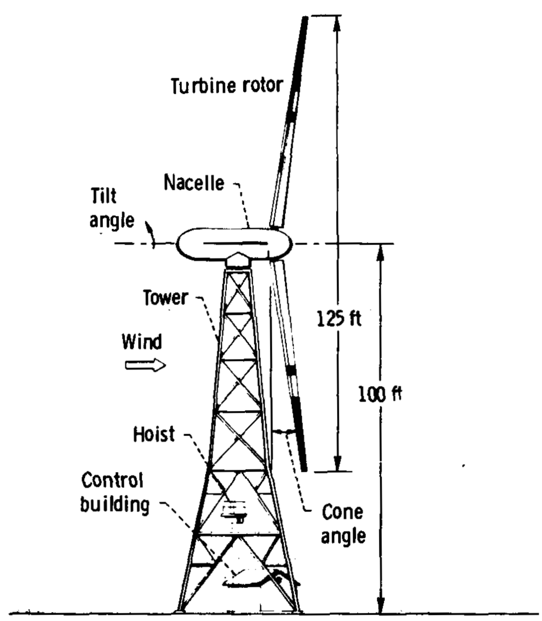


Figure 5. - 200-Kilowatt wind turbine system.

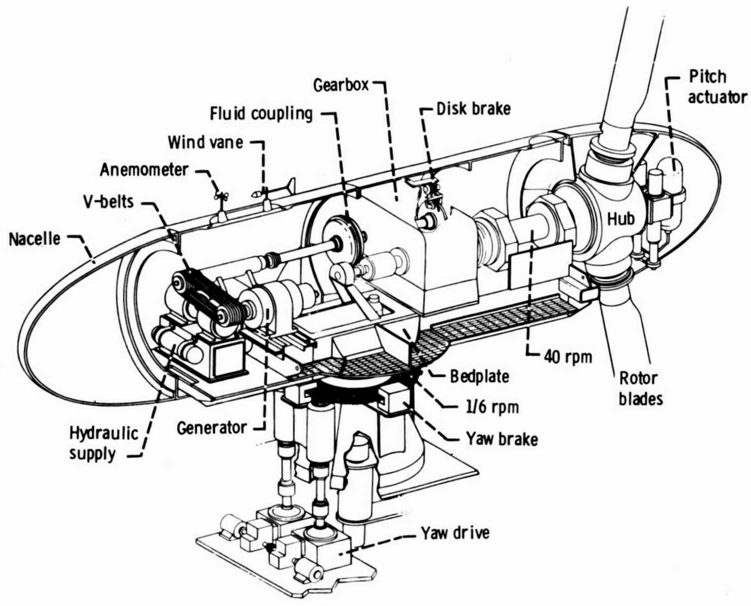


Figure 6. - Cutaway drawing of tower mounted equipment.

Figure 7. - 200-Kilowatt wind turbine assembly.

TABLE I. - 200-KILOWATT WIND TURBINE DESIGN SPECIFICATIONS

Rotor	
Number of blades	2
Diameter, ft	125
Speed, rpm	40
Direction of rotation	Counterclockwise (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulation	Variable pitch
Cone angle, deg	7
Tilt angle, deg	0
Blade	
Length, ft	59.9
Material	Aluminum
Weight, lb/blade	2300
Airfoil	NACA 23000
Twist, deg	26.5
Solidity, percent	3
Tip chord, ft	1.5
Root chord, ft	4
Chord taper	Linear
Tower	
Type	Pipe truss
Height, ft	93
Ground clearance, ft	37
Hub height, ft	100
Access	Hoist
Transmission	
Type	Three-stage conventional
Ratio	45:1
Rating, hp	460
Generator	
Type	Synchronous ac
Rating, kVA	250
Power factor	0.8
Voltage, V	480 (three phase)
Speed, rpm	1800
Frequency, Hz	60
Orientation drive	
Type	Ring gear
Yaw rate, rpm	1/6
Yaw drive	Electric motors
Control system	
Supervisory	Microprocessor
Pitch actuator	Hydraulic
Performance	
Rated power, kW	200
Wind speed at 30 ft, mph (at hub):	
Cut-in	6.9 (9.5)
Rated	18.3 (22.4)
Cut-out	34.2 (40)
Maximum design	125 (150)
Weight (klb)	
Rotor (including blades)	12.2
Above tower	44.9
Tower	44.0
Total	88.9
System life	
All components, yr	30

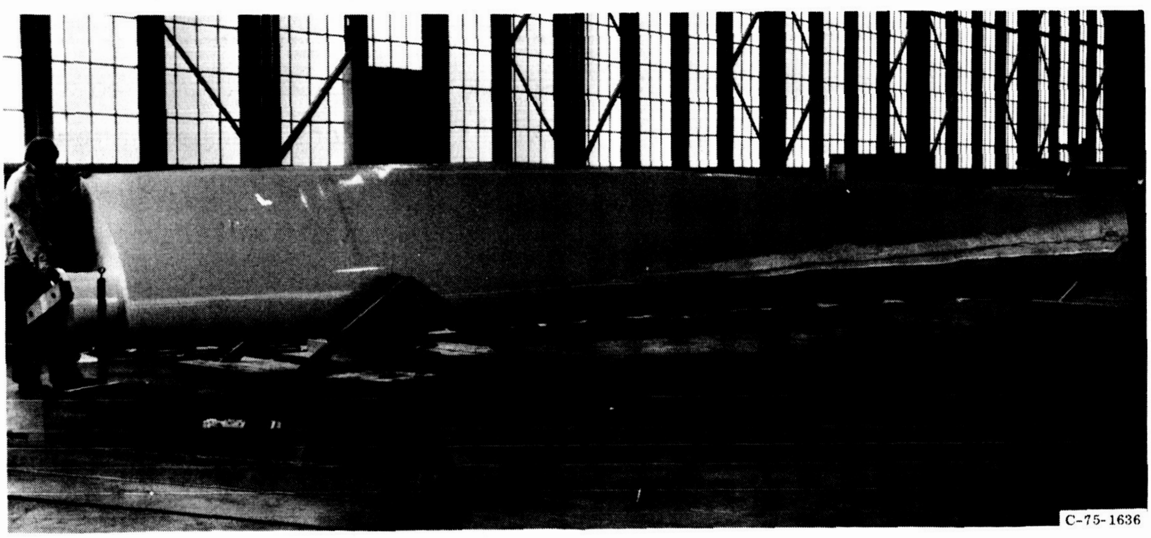


Figure 8. - Rotor blades.

hub. The maximum rate of pitch change is 8^{0} per second.

Drive train assembly. - The drive train assembly that transmits the mechanical power of the spinning rotor to the generator, which generates the electrical power, is shown in figure 6. The hub transmits the high-torque - low-speed power to the gearbox through a low-speed shaft. A 1 to 45 fixed ratio gearbox transmits this power to the high-speed shaft at low-torque - high-speed power. This power is then transferred to the generator through a belt and pulley drive system. The belt and pulley drive system offers the flexibility of making small changes in the nominal 40 rpm of the low-speed shaft, while still maintaining the constant 1800 rpm required by the generator. If test data show that a higher or lower turbine rotor speed would be desirable, the ratio of the shaft speeds may be changed.

Disk brake. - A disk brake system, located on an extension of the high-speed shaft, serves as both a parking brake and a dynamic brake to stop the rotor during an emergency shutdown.

Bedplate. - The bedplate is the steel structural member that supports the entire rotor and nacelle assembly.

Yaw assembly. - The entire machine on top of the tower is supported on a turntable bearing which permits rotation to maintain proper alignment with the wind. Rotation is achieved by driving a large bull gear with two pinion gears as shown in figure 6. The two pinion gears, which are preloaded against each other to increase torsional stiffness, are driven by separate motors and yaw drives. If necessary, yaw control can be achieved by using only one unit. The yaw rate, which is 1/6 rpm, is operational whenever the wind speed exceeds the cut-in wind speed of the wind turbine.

Yaw brake. - The torsional stiffness of the rotating machinery is further increased by activating the three yaw disk brakes shown in figure 6. Even during the yawing motion some brake pressure is applied to damp out any torsional oscillations by maintaining a drag force. Once the machine has aligned itself to the wind, this brake pressure is increased to the maximum.

Fluid coupling. - The function of the fluid coupling on the high-speed shaft is to damp out the power oscillations resulting from the continuously varying wind velocity that the blades

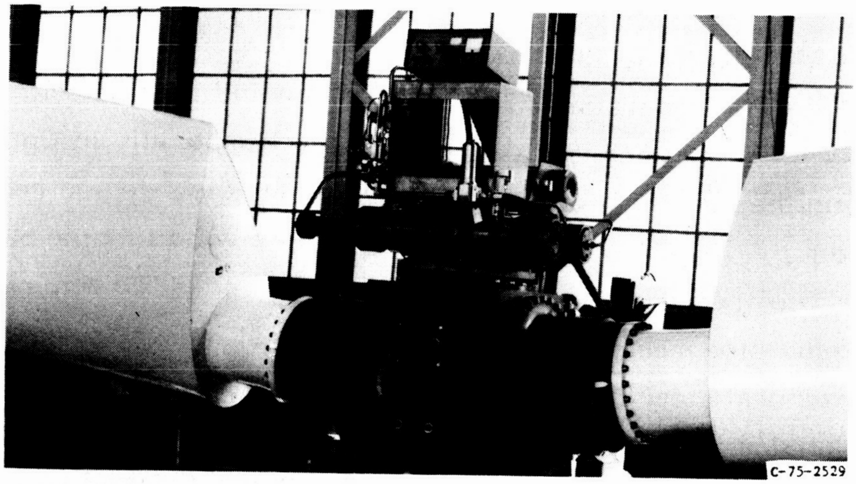


Figure 9. - Hub and pitch change with actuator.

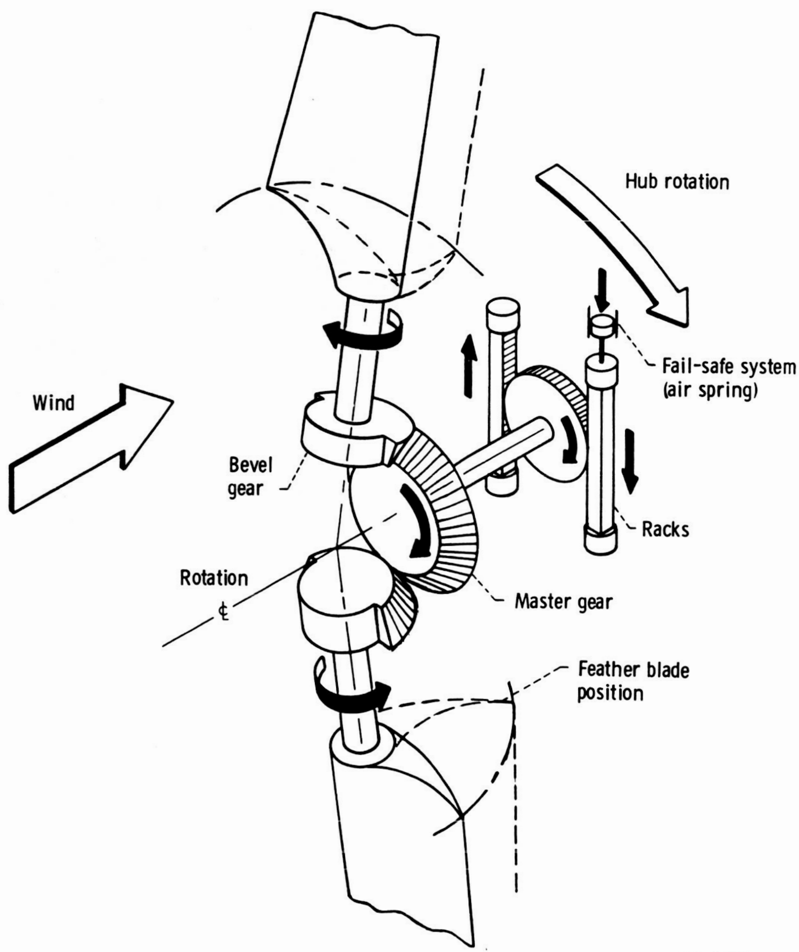


Figure 10. - Blade pitch change diagram.

must withstand due to the tower shadow and the wind shear effects.

Generator. - The generator is a commercially available synchronous machine having the specifications given in table I.

Tower. - The open truss type tower uses round pipe members rather than other structural steel shapes to maximize the airflow through the tower. The increased airflow through the tower reduces the cyclic stresses on the rotor blades as they pass through the tower wake. The tower is anchored to a concrete slab foundation.

Hoist. - Access to the tower mounted components is provided by a cable mounted hoist. This system was selected over conventional stairs to further maximize the airflow through the tower.

control system

The wind turbine control system shown schematically in figure 11 must provide for the safe and reliable operation of the wind turbine at a remote, unattended site. To achieve this, the control system must automatically perform the following three major functions:

- Control production of electric power over a wide range of wind velocities - including all necessary startup, shutdown, and synchronizing activities
- Alignment of the rotor assembly with the wind direction
- Protection against damage due to abnormal operating conditions and/or extreme environmental conditions

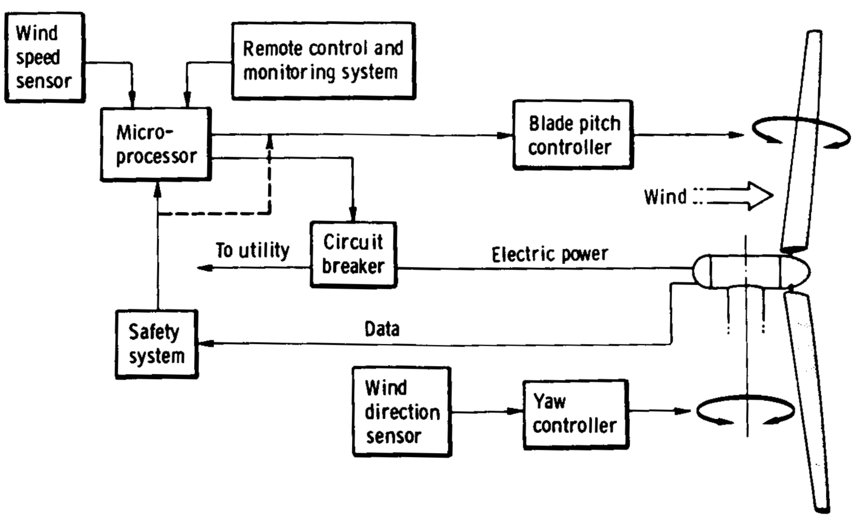


Figure 11. - Simplified wind turbine control schematic.

Each of the five major elements of the control system now discussed is designed to provide high reliability while using proven off-the-shelf components.

Microprocessor. - The microprocessor provides the control logic for operating the wind turbine by continuously monitoring the output of the wind speed sensor. When the wind speed is above the cut-in value, the controller starts the wind turbine, brings it up to speed, and synchronizes it to the utility grid. The microprocessor automatically shuts down and secures the wind turbine whenever the wind speed either drops below cut-in or exceeds cut-out.

Blade pitch controller. - Input from the wind sensor and the generator is fed into the pitch control logic of the microprocessor, which in turn controls blade pitch. Below cut-in wind speed and above cut-out wind speed the blades are feathered. Between cut-in wind speed and rated wind speed the blade pitch is held at a fixed value. For wind speeds between rated and cut-out the blade pitch is controlled to maintain a constant power output of 200 kilowatts.

Yaw controller. - The yaw controller detects wind direction from a wind direction sensor located on top of the nacelle, and it keeps the wind turbine properly aligned with the wind whenever the wind speed is above the cut-in speed. Orienting the wind turbine at wind speeds below cut-in serves no useful propose, and it would decrease the effective service life of the yaw drive system.

Safety system. - The safety system, which is an automatic shutdown system that operates independently of all other wind turbine controls, is designed to protect the wind turbine from catastrophic failure. Various sensors monitor key parameters such as the rotor speed, generator current, electrical load, vibration, yaw error, pitch system hydraulic fluid level, bearing temperatures, gearbox oil temperatures, microprocessor failure, etc. If any sensor signal is outside the normal safe operating range, the safety system will automatically shut down the wind turbine. For example, in the event of rotor overspeed, a speed sensor would issue the command to feather the blades; this automatically stops the rotor by reversing the direction of torque on the rotor. A backup pneumatic system assures that the blades will feather even if the hydraulic system fails. However, if for any reason the blades fail to feather and the machine continues to overspeed, a second totally redundant and physically separate speed sensor acutates an emergency brake which stops the rotor within a few seconds.

Remote control and monitoring system. - The remote control and monitoring (supervisory) system at the utility power dispatcher's center permits manual start-stop control of the microprocessor by the power dispatcher. A digital readout of wind speed, rotor speed, power, VARS, current, and voltage is provided by the supervisory system. In the event of automatic shutdown by the safety system, an indication of overspeed, blades feathered, yaw error, overcurrent, fluid system fault, vibration fault, overtemperature, and microprocessor status associated with the shutdown is provided.

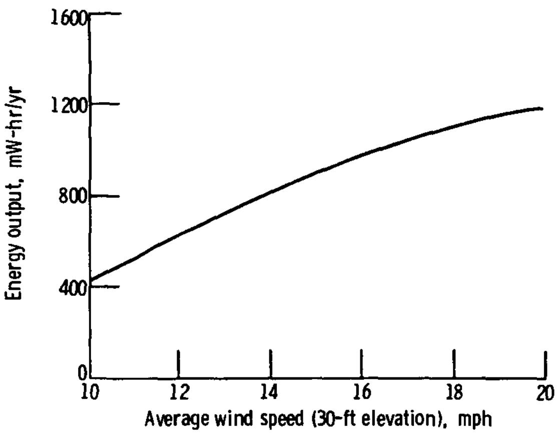


Figure 12. - Annual energy output for 200-kilowatt wind turbine.

annual energy output

The calculated annual energy output for the 200-kilowatt wind turbine operating in various average wind speed environments is shown in figure 12. The average wind speed is the arithmetic average of all hourly wind speeds in a given year at that particular site measured 30 feet above ground level. The energy output is a strong function of the average wind speed, since the available energy in the wind is proportional to the cube of the wind speed. The energy output was computed using a rotor power coefficient of 0.36 and a rotor shaft to generator output efficiency of 0.9. Velocity profile curves for the wind were assumed to be Weibull distributed. Energy capture by the rotor was computed using the wind speed occurring at the hub height of 100 feet. Wind speeds at various elevations are calculated by using the wind shear gradient typical of most of the candidate wind turbine sites. It was estimated that the machine would be shut down 10 percent of the time when the wind velocity was between cut-in and cut-out speeds.

This shutdown time was allowed for both scheduled and unscheduled maintenance.

concluding remarks

The 200-kilowatt wind turbine project described in this report is one phase of the Federal Wind Energy Program managed by the NASA Lewis Research Center for the Department of Energy. The overall objective is to obtain early operation and performance data by operating the four 200-kilowatt wind turbines installed in utility networks representative of future applications. Involving the utilities insures that their needs, concerns, and requirements are understood and met, and it also enables the utilities to gain initial operating experience. The operation of these wind turbines will provide valuable early data to help establish both the technical and economic feasibility of using wind turbines as a supplemental source of energy.

FOR MORE INFORMATION on wind energy and other alternative energy resources, write to:

DOE Technical Information Center
P.O. Box 62
Oak Ridge, Tennessee 37830

A general overview on wind energy is given in the 72-page booklet "Wind Machines," which can be ordered as document 038-000-00272-4 for $2.25 from:

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